Celestial Reference Frames

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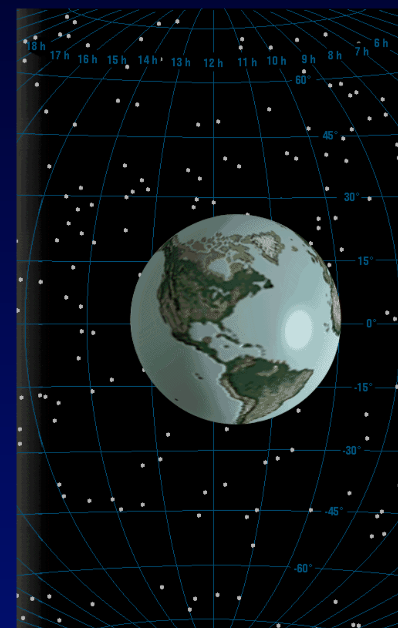
- Introduction to reference systems/frames
- Past
  - FK5 - optical observations of stars
- Present
  - ICRF - radio observations of quasars
  - Other realizations (i.e. optical and infrared)
- Future
  - Improvements in the radio
  - Optical astrometric satellites

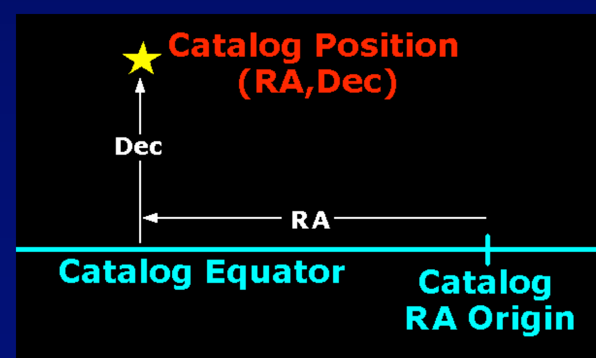
What is a Celestial Reference System?

- Excellent narrative on reference systems and frames
  - G. Kaplan (USNO)
  - http://aa.usno.navy.mil/faq/docs/ICRS_doc.html
- A Celestial Reference System
  - Specifies how a coordinate system will be formed.
  - Defines origin and fundamental planes/axes of the system.
  - Defines constants, models, and algorithms necessary to transform between observable quantities and the reference system.

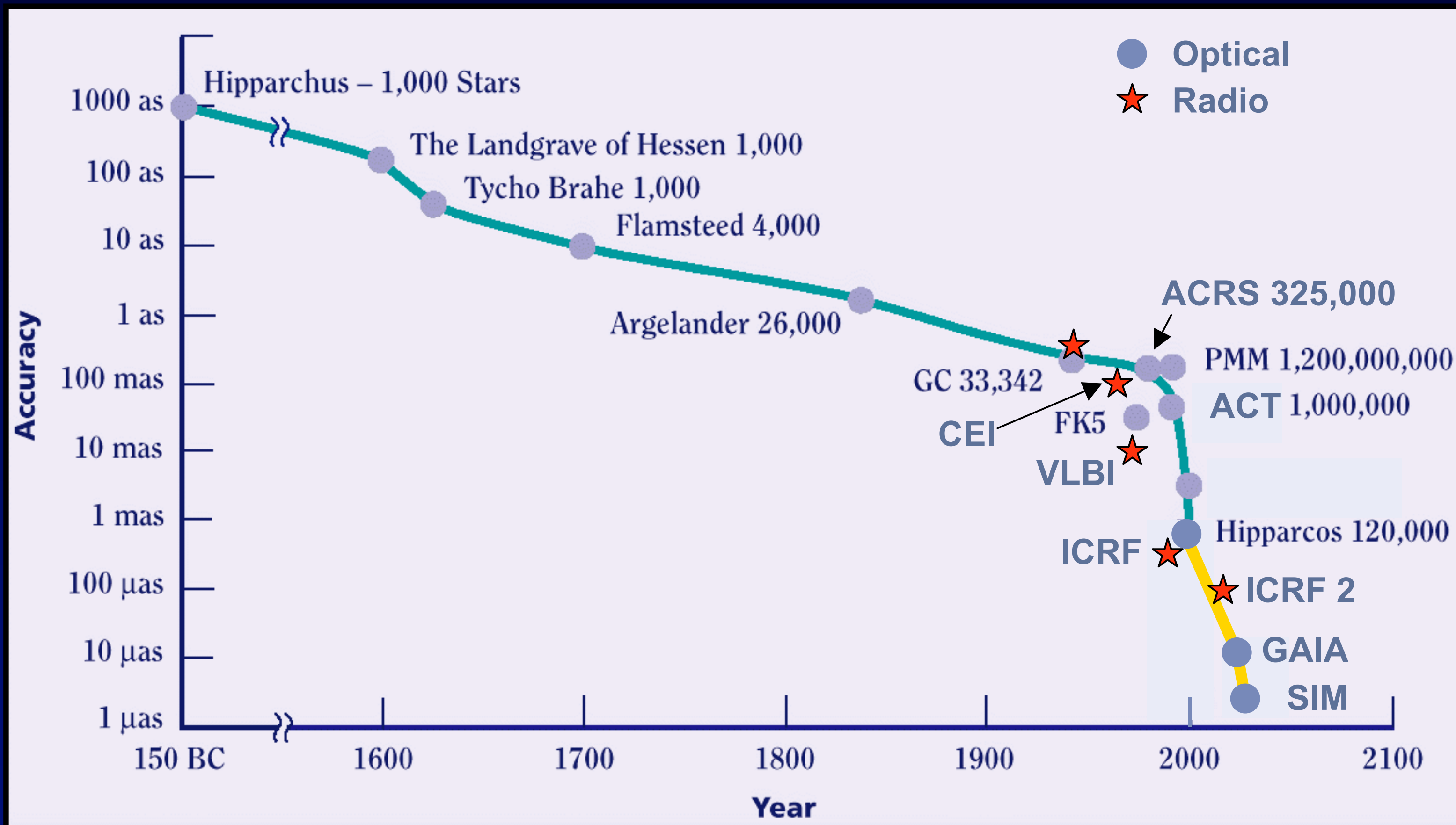
What is a Celestial Reference Frame?

- Set of fiducial points on the sky along with their coordinates.
  - Serves as the practical realization of a reference system.
  - Theoretically only 2 points required.
- In practice:
  - Catalog of precise positions and proper motions of galactic/extragalactic objects.
  - As seen from solar-system barycenter at a specific epoch (usually J2000).
  - Instantaneous coordinates measured as angular distances from the catalog's equator and origin of right ascension (RA and dec).
  - Many objects to reduce systematic/zonal errors.





Astrometric Accuracy vs. Time

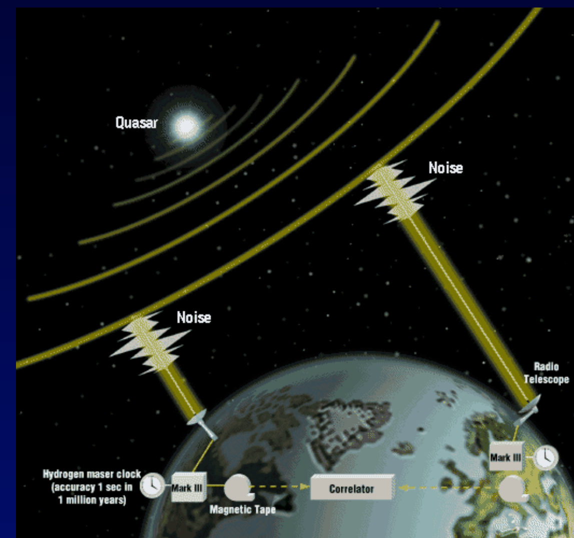


The FK5 System: ICRF Precursor

- Greatly improved version of earlier FK3, FK4 systems
  - Improved star positions and proper motions with reduced systematics.
  - Updated (IAU 1976) models for precession and nutation.
  - Corrections to the zero-point of right ascension applied to agree with equinox of dynamical (planetary) system.
- Catalog
  - 1535 “classical” fundamental stars also in previous FK3, FK4 catalogs (Basic FK5, Fricke et al. 1988, VeARI, 35)
  - 3117 “new” fundamental stars (FK5 Extension, Fricke et al. 1991, VeARI, 35)
  - Mean position accuracy (mean epoch ~1950): ~20 mas
  - Mean proper motion accuracy (mean epoch ~1950): ~0.8 mas/yr

VLBI Astrometric Milestones

- 1960's:
  - Technique of Very Long Baseline Interferometry (VLBI) demonstrated.
  - Used independent local oscillators to link radio telescopes not physically connected.
- 1970's:
  - VLBI position accuracies of ~20 mas achieved.
- Early 1980's:
  - Dual S-band (2.3 GHz) and X-band (8.4 GHz) observations introduced to calibrate ionospheric propagation delay.
  - Position accuracies <0.5 mas achieved.
- Late 1980's
  - Various astrometric catalogs (JPL, GSFC, NGS, USNO/NRL) produced.
  - Catalog position accuracies <1 mas.
  - Program to establish a global reference frame begun.

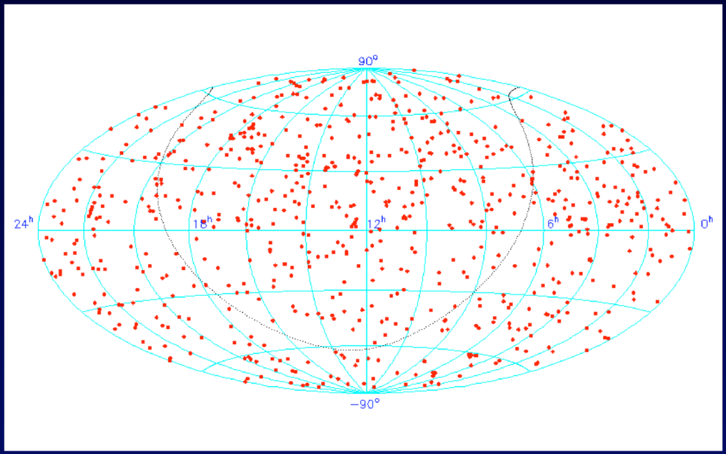


ICRF Timeline

- **1988:** The IAU sets up working groups to establish a new reference frame.
- **1991:** The IAU establishes the theoretical basis for a new reference frame.
- **1994:** The IAU defines the ensemble of fiducial points for a new reference frame as extragalactic objects.
- **1995:** A sub-group of the IAU Working Group on Reference Frames is tasked to construct a new reference frame based on VLBI observations of quasars.
- **1997:** The IAU establishes the ICRS and adopts the ICRF (IAU GA XXIII, Kyoto, Japan).
- **1998:** January 1, the ICRF replaces the FK5 as the fundamental reference frame.

The ICRF

- Ma et al., 1998, AJ, 116, 516
- Observations
  - Aug. 1979 - July 1995
  - 1.6 million group delay obs.
  - Simultaneous S-band (2.3 GHz) and X-band (8.4 GHz).
- 608 Extragalactic radio sources
  - 212 defining - high astrometric quality.
  - 294 candidates - intermediate quality - need more observations.
  - 102 other - excessive position variation, useful for frame densification and optical frame tie.
- Positional accuracies of 212 defining sources: ~250–1000 μas
- Accuracy of frame axes: 20 μas

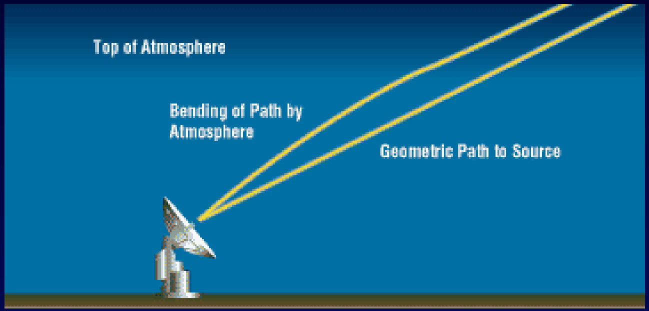


Extensions to the ICRF

- ICRF-Extensions 1 and 2
  - Provide positions for 109 new sources not included in the 1998 definition of the ICRF.
  - Refine positions of "candidate" and "other" sources.
- ICRF Ext.-1 (Gambis, 1999, 1998 IERS Annual Report, Ch. VI)
  - Data: Dec. 1994 - April 1999.
  - 0.6 million new obs. from 861 geodetic/astrometric VLBI sessions.
  - Improved positions for candidate & other sources.
  - 59 new sources added.
  - Positions and errors of 212 defining sources unchanged.
- ICRF Ext.-2 (Fey et al. 2004, AJ, 127, 358)
  - Data: May 1999 - May 2002.
  - 1.2 million new obs. from 400 geodetic/astrometric sessions
  - 50 new sources added.
  - Positions and errors of 212 defining sources unchanged.

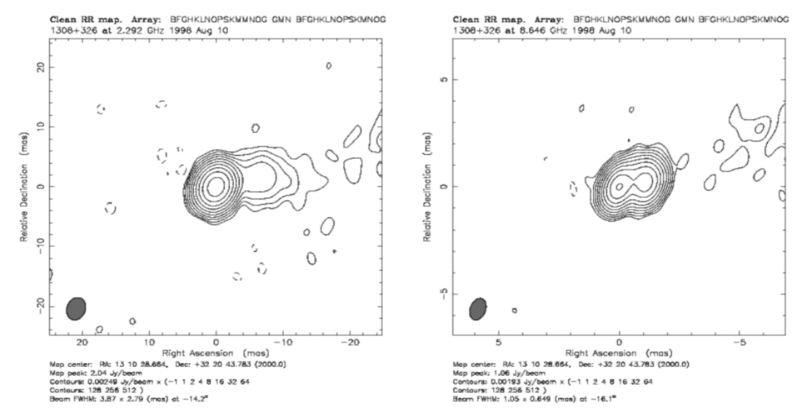
Limitations to the Current ICRF

- Troposphere
  - Error: 150 – 250 μas.
  - Mitigation: improved atmospheric models, WVRs.



- Data acquisition/Instrumentation
  - Error: 50 – 100 μas.
  - Mitigation: incremental improvements, system overhaul.

- Source Structure
  - Error: < 100 μas
  - Source and time dependent.
  - Mitigation: source filtering, source modeling, higher freq. obs.



ICRF Maintenance: Who's Responsible?

ICRS Product Center

ICRF Maintenance/Research

Northern Hemisphere

- Geodetic/Astrometric Experiments (IVS):
  - Geodesy, astrometry.
- VLBA RDV Experiments (USNO, GSFC, NRAO):
  - Astrometry, source imaging/structure
- VLBA Calibrator Surveys (NRAO, GSFC):
  - ICRF densification, calibrators for astronomy.
- EVN Experiments (EVN, Bordeaux Observatory):
  - ICRF densification, calibrators for astronomy.
- K/Q-band VLBA (JPL, GSFC, USNO, NRAO)
  - High frequency (22/43 GHz)
  - Astrometry, source imaging/structure

Southern Hemisphere

- CRF Experiments (IVS):
  - Astrometry, ICRF densification
- LBA (ATNF, USNO):
  - Source imaging/structure

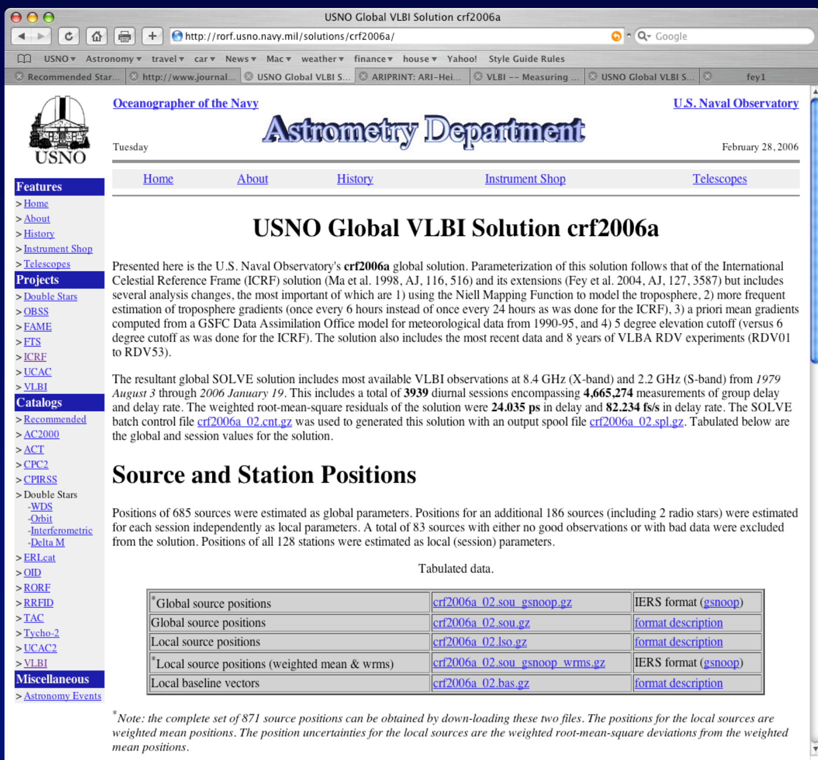
ICRF Research Activities at USNO

- Periodic CRF solutions

http://rorf.usno.navy.mil/solutions/crf2006a/

- Radio Reference Frame Image Database (RRFID)

http://rorf.usno.navy.mil/rrfid.shtml



USNO Global VLBI Solution crf2006a

http://rorf.usno.navy.mil/solutions/crf2006a/

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Miscellaneous: Astronomy Events

USNO Global VLBI Solution crf2006a

Presented here is the U.S. Naval Observatory's **crf2006a** global solution. Parameterization of this solution follows that of the International Celestial Reference Frame (ICRF) solution (Ma et al. 1998, AJ, 116, 516) and its extensions (Fey et al. 2004, AJ, 127, 3587) but includes several analysis changes, the most important of which are 1) using the Niell Mapping Function to model the troposphere, 2) more frequent estimation of troposphere gradients (once every 6 hours instead of once every 24 hours as was done for the ICRF), 3) a priori mean gradients computed from a GSFC Data Assimilation Office model for meteorological data from 1990-95, and 4) 5 degree elevation cutoff (versus 6 degree cutoff as was done for the ICRF). The solution also includes the most recent data and 8 years of VLBA RDV experiments (RDV01 to RDV53).

The resultant global SOLVE solution includes most available VLBI observations at 8.4 GHz (X-band) and 2.2 GHz (S-band) from *1979 August 3* through *2006 January 19*. This includes a total of **3939** diurnal sessions encompassing **4,665,274** measurements of group delay and delay rate. The weighted root-mean-square residuals of the solution were **24.035 ps** in delay and **82.234 fs/s** in delay rate. The SOLVE batch control file crf2006a_02.cnt.gz was used to generated this solution with an output spool file crf2006a_02.spl.gz. Tabulated below are the global and session values for the solution.

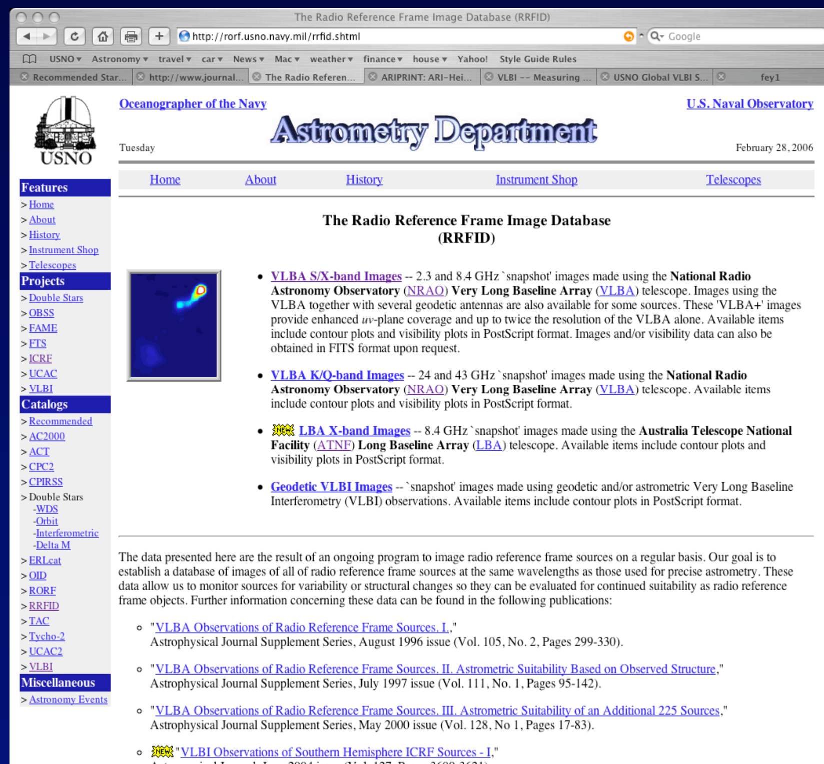
Source and Station Positions

Positions of 685 sources were estimated as global parameters. Positions for an additional 186 sources (including 2 radio stars) were estimated for each session independently as local parameters. A total of 83 sources with either no good observations or with bad data were excluded from the solution. Positions of all 128 stations were estimated as local (session) parameters.

Tabulated data.

*Global source positions	crf2006a_02.sou_gsnoop.gz	IERS format (gsnoop)
Global source positions	crf2006a_02.sou.gz	format description
Local source positions	crf2006a_02.lso.gz	format description
*Local source positions (weighted mean & wrms)	crf2006a_02.sou_gsnoop_wrms.gz	IERS format (gsnoop)
Local baseline vectors	crf2006a_02.bas.gz	format description

**Note: the complete set of 871 source positions can be obtained by down-loading these two files. The positions for the local sources are weighted mean positions. The position uncertainties for the local sources are the weighted root-mean-square deviations from the weighted mean positions.*



The Radio Reference Frame Image Database (RRFID)

http://rorf.usno.navy.mil/rrfid.shtml

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Miscellaneous: Astronomy Events

The Radio Reference Frame Image Database (RRFID)

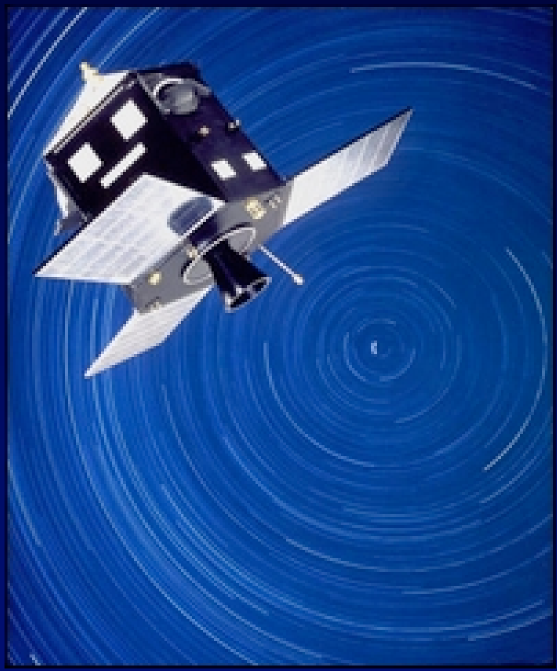
- **VLBA S/X-band Images** -- 2.3 and 8.4 GHz `snapshot' images made using the **National Radio Astronomy Observatory** (NRAO) **Very Long Baseline Array** (VLBA) telescope. Images using the VLBA together with several geodetic antennas are also available for some sources. These 'VLBA+' images provide enhanced *uv*-plane coverage and up to twice the resolution of the VLBA alone. Available items include contour plots and visibility plots in PostScript format. Images and/or visibility data can also be obtained in FITS format upon request.
- **VLBA K/Q-band Images** -- 24 and 43 GHz `snapshot' images made using the **National Radio Astronomy Observatory** (NRAO) **Very Long Baseline Array** (VLBA) telescope. Available items include contour plots and visibility plots in PostScript format.
- NEW **LBA X-band Images** -- 8.4 GHz `snapshot' images made using the **Australia Telescope National Facility** (ATNF) **Long Baseline Array** (LBA) telescope. Available items include contour plots and visibility plots in PostScript format.
- **Geodetic VLBI Images** -- `snapshot' images made using geodetic and/or astrometric Very Long Baseline Interferometry (VLBI) observations. Available items include contour plots in PostScript format.

The data presented here are the result of an ongoing program to image radio reference frame sources on a regular basis. Our goal is to establish a database of images of all of radio reference frame sources at the same wavelengths as those used for precise astrometry. These data allow us to monitor sources for variability or structural changes so they can be evaluated for continued suitability as radio reference frame objects. Further information concerning these data can be found in the following publications:

- "VLBA Observations of Radio Reference Frame Sources. I.," Astrophysical Journal Supplement Series, August 1996 issue (Vol. 105, No. 2, Pages 299-330).
- "VLBA Observations of Radio Reference Frame Sources. II. Astrometric Suitability Based on Observed Structure," Astrophysical Journal Supplement Series, July 1997 issue (Vol. 111, No. 1, Pages 95-142).
- "VLBA Observations of Radio Reference Frame Sources. III. Astrometric Suitability of an Additional 225 Sources," Astrophysical Journal Supplement Series, May 2000 issue (Vol. 128, No 1, Pages 17-83).
- NEW "VLBI Observations of Southern Hemisphere ICRF Sources - I," Astronomical Journal, June 2004 issue (Vol. 127, Pages 3609-3621).

Optical Realization of CRF

- Currently realized through the Hipparcos Celestial Reference Frame (HCRF)
  - Positions and proper motions of ~100,000 stars.
  - Binaries and problem stars vetted.
  - Perryman et al., 1997, A&A, 323, 49
- Catalog accuracy (fiducial points)
  - Median position error 9th mag. stars (mean epoch 1991.25): 0.7–0.9 mas
  - Median proper motion errors: ~1 mas/yr
  - Current degradation: ~15–20 mas



HCRF Link to the ICRF

- Link established through observations of "radio" stars and quasars (Kovalesky et al. 1997, A&A, 323, 620)
  - Heavily weighted toward VLBI observations of 12 stars (Lestrade et al. 1995, A&A, 304,182)
  - Alignment: 0.6 mas at mean HCRF epoch (1991.25).
  - Non-rotating to within 0.25 mas/yr wrt ICRF.
  - Current degradation: ~4 mas.
- Maintenance/improvement of the link.
  - Optical observations of ICRF sources
  - Astrometry on the HCRF via Tycho-2 and UCAC stars.
  - 172 sources: mean std. error ~30 mas (Assafin et al. 2003, AJ, 125, 2728)
  - 18 sources: mean std. error 15–20 mas (Zacharias & Zacharias, ASPC, 338, 184)

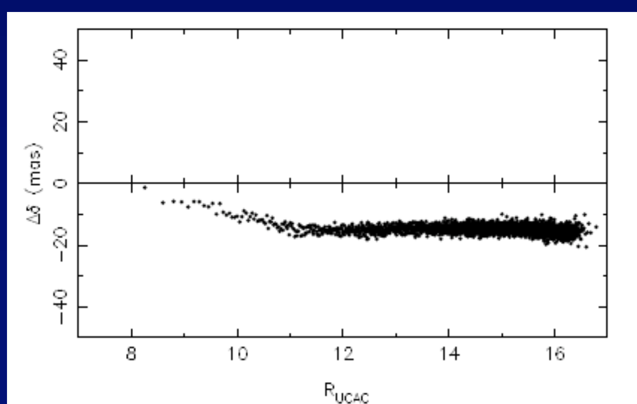
Densification of the Hipparcos Frame

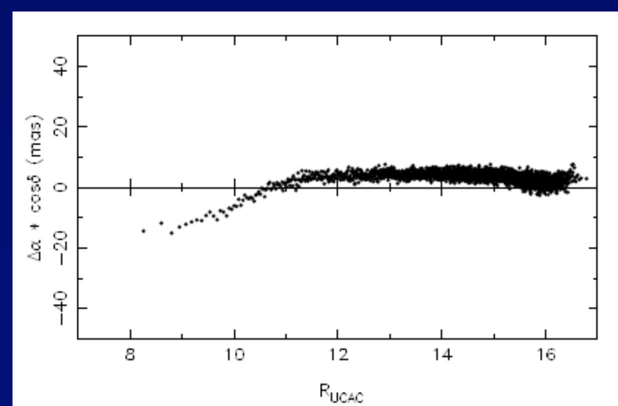
- Tycho, Tycho 2
  - ~2.5 million stars
  - Hipparcos star mapper + ground-based observations
  - Position accuracy: 9th mag. ~20 mas, 12th mag. >100 mas, J2000
  - Proper motion accuracy: 1–3 mas/yr
- Other catalogs
  - Zacharias talk this meeting.

Name of catalog	mag. range	bandpass (approx.)	number of stars	pos.err. (mas)	type	release year	comment
ACR-2	10–17.5	R	1.2 M	26– 60	S	1999	equator. areas
M2000	– 17	V	2.3 M	35–100	S	2001	+11 to +18 decl.
CMC12	9 – 17	r'	6.3 M	36–113	S	2002	–3 to +3 decl.
CMC13	9 – 17	r'	many	35–100	S	2003	+3 to +30 decl.
UCAC1	8 – 16	579-643	27 M	25– 70	(A)	2000	–90 to –15 decl.
UCAC2	8 – 16	...	48 M	20– 70	(A)	2003	–90 to +40 decl.
UCAC3	8 – 16	...	70 M	20– 70	A	2006	all sky
GSC-2.2	12 – 20	B,V	456 M	300	G	2002	posit., photom.
USNO-A2	12 – 20	...	526 M	200	G	2001	posit., photom.
USNO-B	12 – 20	...	1000 M	200	G	2002	incl. proper motions
SDSS	15 – 23	u,b,v,r,z	many	50–150	G	2003	about 5000 sq.deg
2MASS		J,K,H	471 M	60–100	G	2003	infrared survey
NOMAD	-1 – 20	B,V,R,J,H,K	1100 M	10–200	A	2005	merged data set

Extension to the Infrared Frame

- 2 Micron All Sky Survey Project (2MASS)
  - 2 identical 1.3-m telescopes north and south
  - ~470 million point sources, ~1.6 million extended
  - IR photometry: J, H, K bands
  - Position accuracy: 60–100 mas
  - Astrometry on the HCRF linked via Tycho-2 stars.
- Comparison with UCAC/UCAC2 optical catalogs
  - Systematic position differences <20 mas





Future Celestial Reference Frames

- Future VLBI improvements
  - Near term next 5-10 years.
  - Focused primarily on geodesy.
  - Astrometry a secondary consideration.

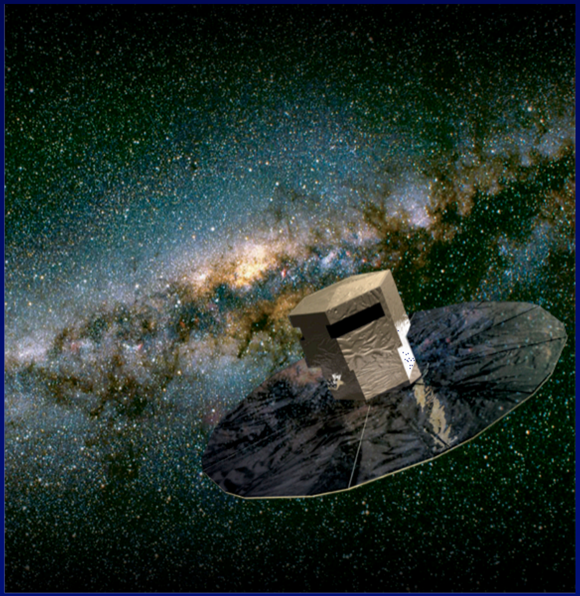
- Astrometric satellite missions
  - Far term 10-20 years.
  - Accurate astrometry is primary goal.
  - Will likely move the ICRF to the optical.

Improvements in the Radio

- Current VLBI network:
  - Technology form 1970's and 1980's.
  - Heterogeneous network of antennas.
  - Developed in many cases for astronomy.
- IVS - WG3 tasked, VLBI 2010 report
  - Primary geodetic goal: long term accuracy of 1 mm on global baselines.
- Future VLBI network:
  - Homogeneous array of many small agile telescopes.
  - Higher (>1 GHz) bandwidth.
  - New feeds, front-ends, back-ends, frequency standards (reduced instrumental errors).
  - Increased observation density (troposphere, source structure).
  - Higher frequencies, X/Ka vs. current S/X (source structure).
  - Improved models (troposphere, source structure).

GAIA Mission

- Launch: Dec. 2011
- Operations: 5 years, continuous scanning
- Catalog: 2020
- Number of objects: ~10^9, (500,000 extragalactic)
- Magnitude Range: $7^{th} - 20^{th}$ m_v
- Accuracy
  - 10^{th} mag. ~ 7 μas
  - 15^{th} mag. ~ 20–25 μas
  - 20^{th} mag. ~ 200-300 μas
- Will likely define the next generation ICRF.
  - 10,000 extragalactic defining sources.
  - Residual frame rotation 0.5 μas/yr.



SIM PlanetQuest Mission

- Launch: 2015
- Operations: 5 years, pointed interferometer
- Catalog: 2021
- Number of objects: $\sim 10^5$ (50-100 extragalactic)
- Magnitude Range: $< 20^{th}$ m_v
- Position Accuracy:
  - 4 μas wide angle (1,300 grid stars)
  - 1 μas narrow angle
  - Quasars 15-20 μas
- Stellar frame axes: 4 μas
- Residual frame rotation: 4 μas/yr
- USNO involvement
  - Key Science Project: *Astrophysics of Reference Frame Tie Objects*, K. J. Johnston, P.I.
  - Key Science Project: *MASSIF,* T. Henry (GSU), P.I.
  - Input catalog and parallel grid star reduction.